Int J Life Cycle Assess (2013) 18:377–391
DOI 10.1007/s11367-012-0501-0

LCA FOR ENERGY SYSTEMS

Life cycle greenhouse gas emissions of electricity generation in the province of Ontario, Canada

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Received: 2 June 2011 / Accepted: 4 September 2012 / Published online: 20 September 2012

Abstract
Purpose This paper assesses facility-specific life cycle greenhouse gas (GHG) emission intensities for electricity-generating facilities in the province of Ontario in 2008. It offers policy makers, researchers and other stakeholders of the Ontario electricity system with data regarding some of the environmental burdens from multiple generation technology currently deployed in the province.
Methods Methods involved extraction of data and analysis from several publically accessible datasets, as well as from the LCA literature. GHG emissions data for operation of power plants came from the Government of Canada GHG registry and the Ontario Power Generation (OPG) Sustainable Development reports. Facility-specific generation data came from the Independent Electricity System Operator in Ontario and the OPG.
Results Full life cycle GHG intensity (tonnes of CO_2 equivalent per gigawatt hour) estimates are provided for 4 coal facilities, 27 natural gas facilities, 1 oil/natural gas facility, 3 nuclear facilities, 7 run-of-river hydro facilities and 37 reservoir hydro facilities, and 7 wind facilities. Average (output weighted) life cycle GHG intensities are calculated for each fuel type in Ontario, and the life cycle GHG intensity for the Ontario grid as a whole (in 2008) is estimated to be 201 t CO_2e/GWh.
Conclusions The results reflect only the global warming impact of electricity generation, and they are meant to inform a broader discussion which includes other environmental, social, cultural, institutional and economic factors. This full range of factors should be included in decisions regarding energy policy for the Province of Ontario, and in future work on the Ontario electricity system.

Keywords Electricity · GHG emissions · Life cycle GHG intensity · Ontario

Responsible editor: Hans-Jürgen Garvens

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1 Introduction

1.1 The issue: greenhouse gas emissions and electricity

Greenhouse gas (GHG) emissions from Canadian electricity-generating facilities have increased 29 % from 94 Mt CO_2 equivalent (Mt CO_2e) in 1990 to 121.5 Mt CO_2e in 2008 (NRCan 2010a). Some suggest that Canada's resource-based economy, cold climate and large geography have made it challenging for the country to meet its GHG emission reduction targets (CE 2010). The challenge is exacerbated in the residential sector by population growth and increasing demand for electric appliances and larger houses. Between 1990 and 2007, energy use in Canadian houses grew by 13 %, and energy use for electric appliances grew by 124 % (NRCan 2010b). Over the same period of time, Canada's population grew by 19 %, and the average floor space for new houses in Canada grew by 10 % (NRCan 2010c). From 2005 to 2020, Canadian population is projected to grow 11 %, and the number of households is projected to grow 20 % to 15 million (NRCan 2010d). Since there are more Canadians, in bigger houses, using more electricity than ever before, it is likely the GHG reductions that relate to the electricity system in Canada will need to come, at least in part, from its cleaner sources of supply.

1.2 Electricity generation in Canada

In 2008, 61 % of electricity generated in Canada came from hydroelectric facilities, while 17 % came from coal, 16 %

from nuclear, 5 % from natural gas and 1 % from heavy fuel oil (Environment Canada 2010a). Some non-hydro renewable sources such as wind, solar and biomass also contributed in smaller amounts. Although the majority of electricity generated in Canada comes from hydroelectric facilities, the electricity supply mix varies considerably within each region of the country. In British Columbia, Manitoba, Quebec and Newfoundland, more than 90 % of electricity is generated at hydroelectric facilities, while in Alberta, Saskatchewan, Ontario, Nova Scotia and New Brunswick, the electricity supply mix is much more diverse. Since the mix of fuel types used to generate electricity varies regionally in Canada, emissions associated with electricity generation also vary considerably between regions. Environment Canada has estimated the average GHG intensity of electricity generation in Canada to be 210 t CO_2e/GWh (tonnes CO_2 equivalent per gigawatt-hour) (Environment Canada 2010a). Table 1 also contains GHG intensities for electricity generation in 2008 by Canadian region.

The GHG intensities shown in Table 1 are based on reported facility data from Environment Canada's GHG emissions reporting program (Environment Canada 2010a). These GHG intensities consider only operation of electricity generators and do not account for the full life cycle GHG emissions associated with electricity generation; emissions associated with construction and decommissioning of the facilities or the mining, refining and transportation of fuel. Furthermore, these GHG intensities are based only on data from generating stations that exceeded the 2008 annual GHG emissions reporting threshold of 100,000 t CO_2e, so generators emitting below this threshold (responsible for 124,000 GWh of electricity in 2008) were not included in the calculation (this threshold was changed to 50,000 t CO_2e per year in 2009 (Environment Canada 2010b)).

1.3 Purpose of the study

This study assesses the different GHG emission intensities from electricity-generating facilities in the province of Ontario. Ontario was chosen as a case study because of the diversity in its electricity supply mix and the likelihood that Ontario's supply mix will need to change within the next 10 to 15 years (OMEI 2010). While conservation and demand-side management provide the greatest benefit in terms of GHG emissions mitigation, this option alone will not bridge the anticipated electricity supply gap in Ontario (Pembina Institute and CELA 2004). Since supply-side management is also necessary, it is important to know the GHG emission intensities from electricity generation facilities in Ontario. These data will help to inform current and future decisions on the construction and operation of electricity generation infrastructure in the province and support efforts to reach Canada's GHG emission reduction targets. These data also enable specific accounting of the GHG impacts of Ontario electricity (or GHG savings resulting from reductions in electricity use) and so are of value in life cycle assessment (LCA) studies of products or processes using this energy carrier. This issue is growing in importance as LCA becomes a more widely used technique, and was the focus of a workshop addressing issues related to electricity LCA data (Curran et al. 2005).

In order to provide GHG emission intensities by electricity generation facility, several public datasets were used. GHG emissions data relating to the operation of power plants came from the Government of Canada GHG registry and the Ontario Power Generation (OPG) Sustainable Development reports. Facility-specific generation data came from the Independent Electricity System Operator (IESO) in Ontario and the OPG. Other data sources used for the upstream and downstream emission factors included existing LCA studies published in academic journals and private sector reports.

Table 2 contains statistics on Ontario's mix of electricity-generating facilities in 2008 (IESO 2010). 2008 was chosen as the reference year for this analysis because this was the most recent year of facility-specific data available in Canada's GHG inventory (Environment Canada 2010b).

1.4 Previous life cycle studies examining GHG emissions from electricity generation

This work fits in the context of several other efforts that characterize life cycle impacts from electricity generation at the regional or national level. Several studies have looked at the life cycle of GHG emissions from various *types* of electricity generation facilities, including Andseta et al. (1998), CERI (2008), Denholm and Kulcinski (2004), Elsam Engineering (2004), Gagnon and van de Vate (1997), Hondo (2005), Kim and Dale (2005), Lenzen (2008), Meier (2002), Pacca (2007), Proops et al. (1996), Weber et al. (2010) and Zhang et al. (2010). There are also LCA studies relating specifically to Ontario generating facilities (Andseta et al. 1998; CERI 2008; Zhang et al. 2010); however, these studies focused on only a few specific facilities or types of facilities, rather than the entire Ontario electricity grid. Table 3 collects the GHG intensity results from the studies investigating multiple types of generating facilities.

One of the challenges in using the data from Table 3 for region-specific emission factors is that the facilities included in these studies are not in Ontario, or do not include all life cycle phases, sometimes omitting the construction and decommissioning of the facilities or upstream fuel production and processing. In order to measure the life cycle GHG emissions of the Ontario electricity grid, it is necessary to

Table 1 Regional Canadian electricity generation by fuel type and GHG intensity in 2008 (Environment Canada 2010a)

Province/territory	Percentage generated by:						GHG intensity (t CO_2e/GWh)
	Hydro	Nuclear	Coal	Natural gas	Heavy fuel oil	Other	
Alberta	3.4	0	82.1	12.5	0	1.9	880
British Columbia	92.1	0	0	7.7	0.2	0	20
Manitoba	97.5	0	1.1	0.1	0.1	1.2	10
New Brunswick	26.0	8.3	25.4	6.0	24.9	9.3	460
Newfoundland & Labrador	97.3	0	0	0	2.7	0	20
Nova Scotia & Prince Edward Island	8.8	0	63.8	8.0	2.5	16.9	790
Ontario	24.1	53.9	14.8	6.3	0.1	0.9	170
Quebec	96.8	2.1	0	0.5	0.2	0.5	2
Saskatchewan	18.6	0	60.1	18.3	0.3	2.7	710
Yukon Territory, Northwest Territories & Nunavut	67.0	0	0	0	33.3	0	60
Canada	59.8	15.9	17.1	4.7	0.9	1.6	210

develop emission factors that take into account variation in construction and operation of, and fuel production for, Ontario electricity generation facilities.

2 Methods

2.1 Goal and scope definition

The purpose of this study is to estimate the life cycle GHG intensity for each electricity generation station located in the province of Ontario. This includes electricity generation facilities using coal, natural gas, oil, nuclear, wind and hydroelectric sources to generate and supply electricity to the Ontario grid. This study assesses and reports GHG emission factors for each phase of the electricity generation life cycle including: (1) the construction of the generation facility; (2) the extraction, production and transportation of the fuel; (3) the operation of the generation facility; and (4) the decommissioning of the facility.

2.2 Life cycle inventory

The list of electricity generation facilities connected to the Ontario grid and their annual electricity generation in 2008 are from IESO (2010). The net electricity output of each facility was either sourced from the OPG Sustainable Development Report (OPG 2009) or was calculated using estimates based on data from similar LCA studies in other jurisdictions as noted below. Yearly operational GHG emissions data were sourced from Canada's GHG registry at the Environment Canada website (Environment Canada 2010b). The emission intensities relating to heavy truck (diesel fuel) transportation in the product life cycle were calculated using the following data from Natural Resources Canada's Office of Energy Efficiency website (NRCan 2010e):

- In 2008, 222 billion tonne-kilometres of freight were moved by heavy truck
- In 2008, 40.1 Mt CO_2e emissions were reported for heavy truck transportation
- Therefore, the GHG intensity for transportation of fuel and materials by heavy truck is 181 tonnes of CO_2e per million tonne-kilometre

When fuel or materials were assumed to be transported by rail, emission factors were sourced from the literature (CERI 2008; Zhang 2010). The emissions associated with the other phases of the life cycle (construction, mining and refining of the fuel, and decommissioning of the facilities) were sourced from the LCA literature on electricity generation facilities.

Table 2 Electricity generation mix in Ontario in 2008 (IESO 2010)

Electricity source	No. of facilities	Generation (GWh)	Percentage of generation (%)
Nuclear	3	83,380	53
Hydro	44	37,839	24
Coal[a]	4	23,115	15
Gas	28	11,325	7
Wind	6	1,155	0.7
Other (mainly biomass)	4	668	0.3

[a]Includes one combined oil and gas facility (Lennox GS)

Table 3 Summary of LCA studies on GHG intensity of electricity generation

Study authors	Boyle et al.	Tremblay et al.	Lenzen	Meier	Hondo	CERI
Date	2003	2005	2008	2002	2005	2008
Region	Int'l	Int'l	Australia	USA	Japan	Ontario
Generation technology	GHG intensity (t CO_2e/GWh)					
Coal–general	800–1,300	940–1,340		1,041	975	1,050
Coal–black, PF fuel			941			
Coal–black, supercritical			863			
Coal–brown, subcritical			1,175			
Natural gas–general	460–1,230	650–770				560
Natural gas–open cycle			751		608	
Natural gas–comb. cycle			577	622	519	
Oil–general	690–870	690–890		875	742	
Nuclear–general	9–100	8–27		17	24	
Nuclear–heavy water			65			2
Nuclear–light water			60			
Hydro–general	2–410	4–2,100		18		
Hydro–run of river						
Hydro–reservoir			15		11	
Wind–general	11–75	16–120	21	14	30	
Solar–general	30–150	81–260	106	39	53	
Biomass–general	37–166			46		

Classifying the facility type was done by sourcing information from the OPG and the Ontario Power Authority (OPA). A complete inventory of the facilities by type and by GHG intensity is provided below.

2.3 Life cycle GHG impact assessment

This study examines the global warming impacts of electricity generation, and the functional unit is 1 GWh of electricity generated. GHG intensity is measured in tonnes of CO_2 equivalent emissions per gigawatt-hour of electricity generated. The United Nations Environment Programme provides the global warming potential (GWP) for each of the six commonly reported GHG emissions which allow the calculation of CO_2 equivalent emissions. The three GHG emissions reported by electricity generation facilities in Canada are carbon dioxide (CO_2, GWP=1 by definition), methane (CH_4, GWP=21) and nitrous oxide (N_2O, GWP=310) (UNEP 2010).

2.4 Assumptions and limitations

A common challenge with life cycle assessment studies is gaining access to publicly available and reliable data (SAIC 2006). Although significant efforts were made to use specific data for each facility within the scope of this study, some data were based on assumptions.

Transportation emission factors in most cases related to the transportation of fuel from mines to refining facilities and later to the electricity generation facilities. In one case (wind facilities), transportation emission factors are related to the transportation of the wind turbine from the manufacturing facility to the final installation site. It was assumed that transportation during the operating phase of the life cycle (i.e. use of vehicles *at* a facility) and the corresponding GHG emissions were included in the GHG emissions data from Environment Canada's GHG reporting program.

Assumptions regarding the GHG emission factors for the construction and decommissioning of facilities were based on data from other LCA studies that assessed similar facilities as those supplying Ontario's grid. The construction and decommissioning emission factors were calculated over the expected service life of a facility. The assumed expected service life of power plants varied with technology: 20 years for wind turbines, 30 years for coal and natural gas, 40 years for nuclear and 100 years for hydro.

GHG emissions for combined heat and power (CHP) facilities need to be allocated between the two energy outputs (electricity and thermal energy). An allocation ratio was assumed for CHP facilities because actual ratios were not available for each CHP facility in Ontario. The electricity allocation ratio used for CHP facilities in this study was calculated using data from the Ontario Power Authority about the energy output capacity (both

electricity and heat) of two CHP facilities in Ontario (East Windsor and Thorold). The average electricity allocation ratio for these two facilities was 0.87, which was the ratio applied to all the CHP facilities in this study.

Since some facilities did not meet the 100,000 t CO_2e annual reporting threshold for Environment Canada's GHG reporting program, an average emissions output per unit of electricity was assumed for these facilities based on the average operating GHG emissions factor for other facilities of the same fuel type.

Capacity factors for generating facilities can change from year to year, which affects GHG intensity. These data reflect 2008 operating conditions and GHG emissions and should be updated on a regular basis.

It was challenging to find data on hydroelectric and wind facilities because there are many unknowns associated with the construction at each individual site, so assumptions were made based on the data available in the literature, as discussed below. There is still poor understanding of the impacts associated with decommissioning of hydroelectric dams and reservoirs, but best estimates were made with data available from studies in other jurisdictions (Gagnon and van de Vate 1997; Tremblay et al. 2005; Pacca 2007). This study evaluated GHG emissions related to electricity generated, not delivered, so electricity lost in transmission and distribution was not included.

Solar and biomass generation technologies also supply electricity to Ontario's grid in relatively small amounts, but they were not included since the data associated with these inputs were not available. Similarly, imports were excluded because generation mix and emissions data from neighbouring jurisdictions were not available. In 2008, imported electricity represented approximately 7 % of Ontario's electricity supply (IESO 2010).

3 Results and discussion

In this section, the GHG intensities for each Ontario electricity generation facility are presented, divided into subsections by fuel type.

3.1 Coal facilities

Electricity generated from coal in Ontario represented approximately 15 % of the total electricity supply mix in 2008 (IESO 2010). From a life cycle perspective, electricity generation from coal facilities in 2008 represented approximately 77 % of the GHG emissions included within the scope of this analysis. In 2008, there were four electricity generation facilities using coal in Ontario. Table 4 shows the electricity generation of coal-powered facilities (IESO 2010) and the facility-specific operational GHG emissions in 2008 (Environment Canada 2010b). This table also shows the net electricity generated (i.e. the electricity used for the facilities' operation is subtracted), as reported in the OPG SD Report (OPG 2009).

The last column in Table 4 shows the facility-specific operational GHG intensity and was calculated by dividing the annual GHG emissions by gross electricity generated for the same year. It is believed that the variation in GHG intensities between coal facilities is in part due to the different types of coal that are used at each facility, but may also have to do with operation of facility-specific equipment and machines (facility trucks, auxiliary boilers, etc.). The average GHG emission factor for the coal category is 1,006 tonnes of CO_2e/GWh.

The upstream emissions associated with the mining, processing and transportation of coal were calculated using values presented in an LCA specific to Ontario coal facilities (Zhang 2010). This LCA assessed the life cycle emissions of the fuel cycle for the Atikokan and Nanticoke facilities (but it did not include emissions associated with the construction and decommissioning of these facilities and did not include an assessment of the two other coal power plants in Ontario). It was assumed that Lambton and Nanticoke used sub-bituminous coal from the USA and that Atikokan and Thunder Bay used lignite coal from Saskatchewan. The emissions associated with the mining and processing of these coal 'pairings' (Lambton & Nanticoke and Atikokan & Thunder Bay) are the same, but small adjustments in the calculations were made for the emissions associated with the transportation phases of the life cycle (due to differences in transportation distances).

Data specific to the construction and decommissioning of each of the four coal-fired power plants in the province of Ontario were not available, so it was assumed that the GHG intensities for these two phases of the life cycle would be similar to those reported in a study of similar facilities in the USA (Meier 2002). The intensities for construction and decommissioning of each of these facilities were assigned values of 1.1 and 0.1 t CO_2e/GWh, respectively (Meier 2002). The complete life cycle GHG intensity for each coal-fired power plant in Ontario is shown in Table 5.

The range of life cycle GHG intensity from coal-fired power plants in the province of Ontario is 1,040 to 1,360 t CO_2e/GWh. The average life cycle GHG intensity for coal facilities is 1,069 t CO_2e/GWh. The GHG intensities for coal-fired power plants fall within the range of those cited in the literature for similar facilities in Ontario and elsewhere (800 to 1,340 t CO_2e/GWh), with the exception of the Atikokan generating station in northern Ontario (1,360 t CO_2e/GWh). The Atikokan facility had very small electricity output (0.2 %) relative to the total electricity generated by all facilities in 2008; therefore, this discrepancy has very little overall impact on the environmental performance of the Ontario grid. In addition, since GHG intensities in this study reflect the emission rates for net electricity generation (i.e. electricity required to operate the facility is subtracted from the total electricity generated), and the electricity

Table 4 Electricity output and GHG emissions for Ontario coal power plants in 2008

Facility name	Gross output (GWh)	Net output (GWh)	GHG emissions (t CO_2e)	GHG intensity (t CO_2e/GWh)
Atikokan	333	313	412,389	1,318
Lambton	6,618	6,544	6,375,227	974
Nanticoke	15,429	15,329	15,413,591	1,006
Thunder Bay	735	702	827,094	1,176
TOTAL - Coal	23,115	22,888	23,028,301	1,006

output for this facility was so low in 2008, a net GHG intensity slightly higher than the expected range cited in the literature is understandable. If we calculate the GHG intensity for this facility with 'gross' electricity output, rather than 'net' electricity output, the value decreases to 1,280 t CO_2e/GWh which is within the range cited.

3.2 Natural gas facilities

During 2008, 27 electricity-generating facilities supplying energy to the Ontario grid were using natural gas turbines. These facilities supplied approximately 7 % of the electricity to the Ontario grid and contributed about 16 % of the GHG emissions from electricity generation facilities in Ontario in 2008. Within this fleet of natural gas facilities, there was a variety of technologies including simple cycle gas turbines (SCGT), combined cycle gas turbines (CCGT) and CHP facilities. SCGTs are "basically jet engines in which the natural gas is burned, creating superheated gas which is then pressurized in pipes and used to drive the turbine" (WISE 2010, p. 84). The more efficient CCGT "couples combustion turbines with steam-based generation technologies to boost the overall efficiency by using the heat coming out of the combustion turbine to generate steam and drive a turbine-generator system" (WISE 2010, p. 84). Since some facilities are more efficient than others, the GHG intensities of facilities within the 'natural gas' category will vary considerably depending on the electricity generation system.

Seven of the 27 natural gas facilities included in this study were CHP, also known as co-generation, facilities. These facilities employ the exhaust heat from the turbine as a co-product. Therefore, a fraction of the emissions needed to be allocated to this thermal energy used in alternative applications. For these seven CHP facilities, an electricity allocation ratio of 87 % was used. This electricity allocation ratio was calculated using energy output capacity data provided by the Ontario Power Authority for two CHP facilities in Ontario: East Windsor (OPA 2010a) and Thorold (OPA 2010b). Although the electricity allocation ratio will likely differ between CHP facilities, ratios were not available for all facilities in Ontario; therefore, the electricity allocation ratio of 87 % was applied to all CHP facilities in this study. Table 6 shows electricity generation, annual GHG emissions and operational emission factors for each natural gas facility examined in this study. The net electricity generation for each natural gas facility was calculated to be 2.54 % less than gross electricity generation data (IESO 2010) and was based on a comparison of total net generation data (CNA 2009) to total gross generation data (IESO 2010) for the total natural gas electricity source category in 2008.

Ten of the 27 natural gas facilities were not used very much in 2008 and therefore they did not surpass the 100,000 t CO_2e annual reporting threshold in the Environment Canada GHG emissions reporting program. For these ten facilities, the average operational intensity of the other reporting SCGT and CCGT facilities (435 t CO_2e/GWh) was used in order to complete Table 6. For CHP facilities that did not report GHG emissions, the average 435 t CO_2e/GWh intensity was multiplied by 87 % resulting in a GHG emissions intensity of 378 t CO_2e/GWh. This adjustment was made to the 'CHP average' emissions factor to account for emissions associated with thermal energy output.

The upstream emissions associated with the recovery, processing, transportation and storage of the natural gas

Table 5 Life cycle GHG intensity for Ontario coal-fired power plants

Facility name	GHG intensity (t CO_2e/GWh)						
	Const.	Mining and process.	Trans.	Fac. oper.	Comb.	Decomm.	Full life cycle
Atikokan	1.1	29	12	80	1,238	0.1	1,360
Lambton	1.1	22	43	11	963	0.1	1,040
Nanticoke	1.1	22	40	7	999	0.1	1,069
Thunder Bay	1.1	29	15	51	1,125	0.1	1,223

Table 6 Electricity output and GHG emissions for Ontario natural gas power plants in 2008

Facility name	Gross output (GWh)	Net output (GWh)	GHG emissions (t CO_2e)	GHG intensity (t CO_2e/GWh)
Brighton Beach	944	921	348,804	379
Cardinal	1,147	1,119	511,648	457
Destec	428	417	N/A	435
DOW Chemical	152	148	N/A	435
DPNTMTLND	59	58	N/A	435
East Windsor (CHP)	0	0	N/A	378
Fort FrancSWC (CHP)	505	493	378,474	669
Greenfield	647	631	193,668	307
GTAA (CHP)	174	170	91,958	471
Halton Hills	0	0	N/A	435
Lake Superior	369	360	150,707	419
NP Iroqfalls (CHP)	686	669	357,187	464
NP Kirkland	323	315	207,966	660
Portlands	117	114	12,553	110
SITHE Goreway	34	33	N/A	435
STCLAIR	0	0	N/A	435
TA Douglas	855	834	368,158	435
TA OHSC	480	468	191,669	409
TA Sarnia (CHP)	1,497	1,460	1,113,137	663
TA Windsor	358	349	185,970	533
TC Kap	281	274	100,224	366
TC Nipigon	270	263	N/A	435
TC North Bay	259	253	N/A	435
TC PL Tunis	292	285	100,185	352
THOROLD (CHP)	0	0	N/A	378
West Windsor	815	795	379,459	477
Whitby (CHP)	263	256	156,493	531
Total–natural gas	10,955	10,677	4,848,258	435[a]

[a]Average GHG intensity of SCGT and CCGT facilities that reported GHG emissions

were based on the values provided in a study that examined a natural gas power plant in Ontario (Zhang et al. 2010). These upstream emissions are based on the assumption that natural gas for Ontario facilities comes from the Canadian province of Alberta and that 0.25 % of the gas is lost in transportation (a figure from NRCan GHGenius database, as reported in Zhang et al. 2010).

Data specific to the construction and decommissioning of each of the natural gas power plants in the province of Ontario were not available, so it was assumed that the emissions for these two phases of the life cycle would be similar to those reported in a study of natural gas facilities in the USA (Meier 2002). The intensities for construction and decommissioning of each of the natural gas facilities were then assigned values of 1.9 and 0.02 t CO_2e/GWh, respectively (Meier 2002). For the CHP facilities, the GHG intensities were multiplied by 87 % to account for the GHG emissions associated with the production of heat energy. The complete life cycle GHG intensities for each natural gas power plant in Ontario are shown in Table 7.

In the natural gas part of this analysis, there is one facility that is a clear outlier in the data shown in Table 7. The Portlands facility has a very low life cycle GHG intensity of only 154 t CO_2e/GWh. This plant did not come online until more than half way through the reference year; therefore, there are likely some issues with regard to the emissions data or the electricity generation data that were reported. After removing the Portlands outlier for reasons explained above, the range of GHG intensities for electricity generation from natural gas facilities is 351 to 707 t CO_2e/GWh. The average life cycle GHG emission factor of natural gas facilities, after removing Portlands, is 497 t CO_2e/GWh.

The average GHG intensity (497 t CO_2e/GWh) for natural gas-fuelled power plants in this study is at the lower end of the range found in the literature (460 to 1,230 t CO_2e/GWh). Part of this might be explained in the assumption that was used with regard to the amount of methane released during the recovery and transportation phases of the life cycle. In this study, we assumed that 0.25 % of the gas

Table 7 Life cycle GHG intensity for Ontario natural gas power plants

Facility name	GHG intensity (t CO_2e/GWh)							
	Const.	Recov.	Process.	Trans. & stor.	Oper.	Comb.	Decom.	Full life cycle
Brighton Beach	1.9	14	16	12	10	369	0.02	423
Cardinal	1.9	14	16	12	11	446	0.02	501
Destec	1.9	14	16	12	28	407	0.02	479
DOW Chemical	1.9	14	16	12	28	407	0.02	479
DPNTMTLND	1.9	14	16	12	28	407	0.02	479
East Windsor (CHP)	1.65	12	14	10	24	354	0.02	417
Fort FrancSWC (CHP)	1.65	12	14	10	17	652	0.02	707
Greenfield	1.9	14	16	12	8	299	0.02	351
GTAA (CHP)	1.65	12	14	10	11	460	0.02	510
Halton Hills	1.9	14	16	12	28	407	0.02	479
Lake Superior	1.9	14	16	12	11	408	0.02	463
NP Iroqfalls (CHP)	1.65	12	14	10	11	453	0.02	503
NP Kirkland	1.9	14	16	12	16	644	0.02	704
Portlands	1.9	14	16	12	3	107	0.02	154[a]
SITHE Goreway	1.9	14	16	12	28	407	0.02	479
STCLAIR	1.9	14	16	12	28	407	0.02	479
TA Douglas	1.9	14	16	12	28	407	0.02	479
TA OHSC	1.9	14	16	12	10	399	0.02	453
TA Sarnia (CHP)	1.65	12	14	10	16	647	0.02	702
TA Windsor	1.9	14	16	12	14	519	0.02	577
TC Kap	1.9	14	16	12	9	357	0.02	410
TC Nipigon	1.9	14	16	12	28	407	0.02	479
TC North Bay	1.9	14	16	12	28	407	0.02	479
TC PL Tunis	1.9	14	16	12	9	343	0.02	396
THOROLD (CHP)	1.65	12	14	10	24	354	0.02	417
West Windsor	1.9	14	16	12	11	466	0.02	521
Whitby (CHP)	1.65	12	14	10	13	518	0.02	569

[a] Portlands is an outlier and is further explained in the text.

was lost during the upstream phases of the natural gas life cycle (an assumption taken from the Canadian government's GHGenius database as cited in Zhang 2010). However, in the USA, it is assumed that 1.32 % of gas is lost during the upstream phases of the life cycle (Zhang 2010), which would result in higher life cycle GHG intensities for each natural gas-generating station. This difference would result in an increase of 28 t CO_2e/GWh or a GHG intensity of 525 t CO_2e/GWh for the 'natural gas' category in Ontario. In addition, nearly all natural gas facilities in Ontario use either 'combined heat and power' or 'combined-cycle' generation technology, rather than the less efficiency 'simple-cycle generation technology' that may be used in other jurisdictions more widely.

A sensitivity analysis was also conducted on the change in GHG emission factor resulting from a change in the electricity allocation factor for the seven CHP facilities in Ontario. This analysis illustrates (in Table 8) the impact of varying the allocation factor ±10 % from the 87 % nominal value.

Table 8 Sensitivity of GHG intensity to electricity allocation factor for CHP facilities

Facility name	Life cycle GHG intensity (t CO_2e/GWh)		
	Electricity allocation factor		
	77 %	87 %	97 %
East Windsor	369	417	464
Fort Franc SWC	627	707	788
GTAA	451	510	568
NP Iroqfalls	445	503	560
TA Sarnia	621	702	782
THOROLD	369	417	464
Whitby	504	569	634

Table 9 Electricity output and GHG emissions for Lennox GS oil and gas facility in 2008

Facility name	Gross output (GWh)	Net output (GWh)	GHG emissions (t CO_2e)	GHG intensity (t CO_2e/GWh)
Lennox GS	370	278	288,674	1,038

3.3 Combined oil and natural gas facilities

One electricity generation facility in Ontario merits its own section because it uses both residual fuel oil and natural gas. Lennox Generating Station (GS) is Canada's largest oil and gas-fuelled generating station with a total output capacity of 2,100 MW (OPG 2010a). Although that is "enough electricity to meet approximately 8 % of the electricity needs in the province of Ontario" (OPG 2010a), Lennox GS represented less than 0.3 % of electricity generated by all Ontario facilities supplying the grid in 2008 (IESO 2010). Still, given the two sources of fuel and the large capacity, it is worth understanding the facility-specific GHG intensity for this facility. Table 9 shows the gross electricity generation (IESO 2010), net electricity generation (OPG 2009), annual GHG emissions (Environment Canada 2010b) and GHG intensity for the Lennox GS facility in 2008.

Since it is expected that oil- and natural gas-fuelled power plants generally have lower GHG intensities than coal-fired power plants, the operational intensity for Lennox shown in Table 9 is suspiciously high. In 2008, the proportion of electricity generated that was required to operate the Lennox facility was extremely high (25 %). If gross electricity, rather than net electricity, is used to calculate the operational intensity of this facility, the GHG intensity then becomes 780 t CO_2e/GWh. In years when the total generation is low at Lennox GS (as in 2008) and the *proportion* of total electricity generation that is required to operate the station is high, the GHG intensity is increased substantially (OPG 2010b)

Since there are two sources of fuel for this facility, calculating the upstream GHG emission factor is slightly more complicated than for other facilities in this study. We know from the analysis of natural gas facilities that the total upstream GHG intensity is approximately 42 t CO_2e/GWh. In a study of oil facilities in the USA, it was found that the typical upstream GHG intensity for electricity generation from oil-fuelled power plants was 42.5 t CO_2e/GWh (Meier 2002). Therefore, the upstream emission factor for Lennox GS was assumed to be 42 t CO_2e/GWh. The construction and decommissioning GHG intensities were also assumed based on U.S. data for similar facilities (Meier 2002). The full life cycle GHG intensity for Lennox GS is shown in Table 10.

3.4 Nuclear facilities

Nuclear power supplied approximately 53 % of the electricity generated in Ontario in 2008. The life cycle GHG emissions from nuclear electricity generation in 2008 were calculated to be approximately 400,224 t CO_2e for all three nuclear power plants in the province, representing 1.26 % of the total GHG emissions associated with electricity generation in Ontario. Nuclear facilities supply a large proportion of the base load electricity in Ontario because they have low operating costs and slow response times to peaking demand (WISE 2010). Therefore, these facilities have high electricity outputs (IESO 2010; OPG 2009) and relatively low operational GHG emissions, as shown in Table 11.

The source for net electricity output was the 2009 OPG Sustainable Development Report (OPG 2009); however, since Bruce A & B are facilities that are managed by the privately owned company Bruce Power rather than the Crown corporation OPG, the net electricity output for Bruce A & B was not available and so was estimated using the same net electricity proportion from Darlington and Pickering A & B. In addition, the annual operating GHG emissions of each nuclear facility did not meet the 100,000 t CO_2e reporting threshold in the Environment Canada GHG emissions reporting program, so alternate sources were used to calculate the operating emission factor for these facilities. The OPG Sustainable Development Report provided annual CO_2 emissions for the OPG-owned and operated nuclear facilities (Darlington and Pickering A & B), and these data were used to calculate the operational emission factor of 0.2 t CO_2e/GWh (CH_4 and N_2O emissions were not reported in the OPG Sustainable Development Report). It was assumed that the GHG emissions associated with the operation of nuclear facilities also include the emissions associated with operating the on-site storage facilities for nuclear waste.

Table 10 Full life cycle GHG intensity for Lennox GS oil and gas facility

Facility name	GHG intensity (t CO_2e/GWh)					
	Const.	Upstream	Oper.	Comb.	Decom.	Full life cycle
Lennox GS	1.5	42	258	780	0.5	1,082

Table 11 Electricity output and GHG emissions for Ontario nuclear power plants in 2008

Facility name	Gross output (GWh)	Net output (GWh)	GHG emissions ($t\ CO_2e$)	GHG intensity ($t\ CO_2e/GWh$)
Bruce A & B	35,300	35,124	N/A	0.2
Darlington	28,861	28,840	N/A	0.2
Pickering A & B	19,219	19,123	N/A	0.2
Total–nuclear	83,380	83,087	N/A	0.2

The nuclear fuel cycle data needed to calculate and report the upstream GHG emission factors were found in a Canadian Energy Research Institute (CERI) report. The purpose of this report was to conduct a comparative life cycle assessment (LCA) of base load electricity generation in the province of Ontario (CERI 2008). This particular study did not report the emissions associated with each nuclear facility in Ontario; however, since all nuclear facilities in this study use Canada Deuterium Uranium (CANDU) heavy water reactors, and all the uranium used in these facilities comes from Saskatchewan, it is reasonable to assume that there will not be much variation in GHG emissions between Ontario nuclear facilities.

The GHG intensities for construction and decommissioning of nuclear facilities were found in a study that examined the global warming impact of CANDU nuclear facilities (Andseta et al. 1998). The full life cycle intensities for the Ontario nuclear power plants are shown in Table 12.

The GHG intensity for Ontario's nuclear fleet is on the low end of the range cited in the literature for the nuclear source category. It is likely low because the uranium used in CANDU heavy water reactors (HWR) does not require fuel enrichment, which is an energy-intensive process, and thus increases the GHG emission factors in other jurisdictions around the world that use light water reactors. In addition, since this study included the full life cycle GHG emissions from construction and decommissioning of the power plants, the results here are slightly higher than the results from another Ontario study (2 $t\ CO_2e/GWh$) (CERI 2008).

3.5 Hydroelectric facilities

During the reference year of this study, there were 37 hydroelectric facilities generating electricity with flooded reservoirs and 7 facilities operating as run-of-river stations in the province of Ontario (IESO 2010). Hydroelectric plants with reservoirs generally have larger electricity-generating capacity than smaller run-of-river plants that do not have the capacity to store water. None of the hydroelectric facilities exceeded Environment Canada's annual GHG emissions reporting threshold of 100,000 $t\ CO_2e$; therefore, GHG intensities for these 44 facilities were based on literature reporting GHG emission factors for similar facilities. Table 13 provides a list of all the hydroelectric generating stations providing electricity to the Ontario grid in 2008, as well as their respective electricity output for the year (IESO 2010).

GHG emissions associated with the life cycle of hydroelectric facilities occur mainly from: (1) energy and materials for the construction of the facility (2) the decomposition of biomass in the reservoir and (3) the energy required, and additional release of biomass-related GHGs, from the decommissioning of the facility. The decomposition of biomass in the reservoir has an impact on global warming because trees, plants, soils and other types of biomass become trapped in the reservoir, and they decompose under water, eventually releasing carbon dioxide (CO_2) and methane (CH_4) into the atmosphere. The amount of greenhouse gases released into the atmosphere from the decaying of biomass in the reservoir depends largely on two variables: (1) the type of ecosystem flooded and (2) the depth of the reservoir (Gagnon and van de Vate 1997). The literature indicates that GHG emissions from decaying biomass in reservoirs are much lower in colder climates because cold water and ice decrease the decay rate (Gagnon and van de Vate 1997). Tremblay et al. (2005) found that the GHG emission factor for reservoirs in tropical ecosystems can be up to 2,100 $t\ CO_2e/GWh$. In boreal ecosystems, like those in

Table 12 Full life cycle GHG intensity for Ontario nuclear power plants

Facility name	GHG intensity ($t\ CO_2e/GWh$)							
	Const.	Mining & mill.	Refine & conv.	Fuel fab.	Trans.	Oper.	Decom.	Full life cycle
Bruce A & B	2.2	1.6	0.1	0.1	0.1	0.2	0.6	4.8
Darlington	2.2	1.6	0.1	0.1	0.1	0.2	0.6	4.8
Pickering A & B	2.2	1.6	0.1	0.1	0.1	0.2	0.6	4.8

Table 13 Electricity output and full life cycle GHG intensity of Ontario hydroelectric facilities in 2008

Facility name	Facility rating (MW)	Gross output (GWh)	Full life cycle GHG intensity (t CO_2e/GWh)
Run-of-river facilities			
ABKENORA	10	0.14	1.5
APIROQUOIS	30	66.84	1.5
CARMICHAEL	20	83.11	1.5
CLERGUE	52	375.64	1.5
DA WATSON	22	394.82	1.5
LONGSAULTE	14	110.73	1.5
UMBATAFALLS	23	12.55	1.5
Reservoir facilities			
AGUASABON	40	334.76	22.5
ALEXANDER	66	551.02	22.5
ARNPRIOR	82	189.57	22.5
AUBREYFALLS	162	189.60	22.5
BARRETT	176	413.15	22.5
BECK1	498	1,462.65	22.5
BECK2	1499	10,097.82	22.5
BECK2 PGS	174	147.95	22.5
CAMERONFALLS	77	692.64	22.5
CANYON	349	1,554.36	22.5
CARIBOUFALLS		640.34	22.5
CHATSFALLS	96	559.97	22.5
CHENAUX	144	840.33	22.5
DECEWFALLS	144	1,137.62	22.5
DECEWND1	23	111.14	22.5
DESJOACHIMS	429	2,651.26	22.5
GARTSHORE	23	371.28	22.5
HARMON	219	617.22	22.5
HOLDEN	243	1,366.09	22.5
HOLINGSWTH	23	120.31	22.5
KAKABEKA	25	189.82	22.5
KIPLING	233	622.13	22.5
LITTLELONG	204	552.32	22.5
LOWERNOTCH	140	493.48	22.5
MACKAYGS	62	205.10	22.5
MANITOUFALLS	42	496.86	22.5
MTNCHUTE	170	405.33	22.5
OTTERRAPIDS	182	761.57	22.5
PINEPORTAGE	140	1,088.25	22.5
RAYNER	46	32.72	22.5
REDROCK	41	193.41	22.5
SAUNDERS	1045	5,527.07	22.5
SILVERFALLS		316.61	22.5
SMOKY	268	363.37	22.5
STEWARTVLE	182	419.16	22.5
WELLS	239	381.44	22.5
WHITEDOG		443.52	22.5
Total–Hydro		37,839	22

Ontario, it was found that the average GHG emission factor was 15 t CO_2e/GWh (Gagnon and van de Vate 1997; Tremblay et al. 2005). Gagnon and van de Vate (1997) found that 2.5 t CO_2e/GWh were associated with the materials and energy required to construct the dam and generation facility, and approximately 12.5 t CO_2e/GWh were attributed to the GHG emissions associated with decaying biomass. These studies did not include the GHG emissions associated with the decommissioning of the reservoir.

Pacca (2007) examined the potential global warming impact of decommissioning hydroelectric dams and reservoirs and found that the GHG emissions from the decommissioning phase could emit three times more GHG emissions than the construction phase due to sediment built up in the reservoir releasing methane into the atmosphere when the reservoir is removed. So, for this study, it is assumed that the emissions factor for the decommissioning of Ontario's hydroelectric dams is 7.5 t CO_2e/GWh (=2.5 t CO_2e/GWh × 3).

Since run-of-river facilities do not require flooding of reservoirs, there are no additional GHG emissions associated with the decay of biomass. The GHG emission factors for these facilities were calculated using data for run-of-river facilities in Québec and Switzerland (Gagnon and van de Vate 1997), 0.9 t CO_2e/GWh for construction and 0.6 t CO_2e/GWh for decommissioning, totalling 1.5 t CO_2e/GWh for the full life cycle. Full life cycle GHG intensities for each hydro facility are contained in Table 13.

Since the life cycle GHG intensities for the hydroelectric facilities in this study were based on findings from the literature (rather than on specific data from Ontario sites), it is not surprising that the findings are within the range found in the literature. However, the weighted average emission factor applied to the hydroelectric category in this analysis (22 t CO_2e/GWh) is on the lower end of the range found in the literature (2 to 2,100 t CO_2e/GWh). The primary reason for lower GHG emissions from Ontario facilities is the colder climate and thus reduced decomposition of biomass in the reservoirs relative to those in warmer and tropical ecosystems. In addition, since the data for Ontario hydroelectric facilities in this study came largely from studies relating to the neighbouring jurisdiction of Québec, these assumptions seem reasonable.

3.6 Wind facilities

In 2008, electricity generation from wind turbines represented a very small proportion (<1 %) of the supply mix in Ontario (IESO 2010); however, this is still an important electricity source category for examination because the Government of Ontario plans to increase the number of wind electricity stations in the coming years (OMEI 2010). In 2008, six wind farms supplied electricity to the Ontario grid. The electricity output and the types of turbines used at each wind farm are shown in Table 14.

The GHG emissions associated with wind electricity are primarily from the manufacturing and transportation of the materials and installation of the wind turbines. Turbines that are installed off-shore generally are more energy- and material-intensive and thus have higher life cycle GHG intensities (Elsam Engineering 2004). In order to calculate the full life cycle GHG intensity of each wind farm in Ontario, several assumptions were made with the help of LCAs from other jurisdictions. In one study, the life cycle GHG emissions for onshore and offshore Vestas V80 wind turbines in Denmark were calculated (Elsam Engineering 2004). Since one of the wind farm sites in Ontario (Kingsbridge) is using the same model of wind turbine (Vestas V80 2 MW), this was an appropriate basis for the analysis of this source category. The construction/installation and operational GHG intensities for this model turbine, assuming a 20-year expected lifetime, were 6.97 and 0.74 t CO_2e/GWh, respectively. These intensities for construction and operation life cycle phases were applied to all wind farms in this analysis and are shown in Table 15.

The GHG emissions associated with the transportation of the turbines from the manufacturing facilities to the generation sites were calculated based on the weight of the turbine materials (Elsam Engineering 2004), the number of turbines at each site (available on the OPA website), the distance travelled (based on estimates for each site) and the transportation emissions factor calculated in the "Section 2" of this

Table 14 Electricity output from Ontario wind farms in 2008

Facility name	Type of facility	Gross electricity output (GWh)
AMARANTH	88 GE 1.5 MW sle turbines	227.6
KINGSBRIDGE	22 Vestas 2 MW V80 turbines	118.2
PORT ALMA	44 Siemens 2.3 MW Mark II turbines	117.1
PORT BURWELL	66 GE 1.5 MW sle turbines	253.8
PRINCEFARM	126 GE 1.5 MW sle turbines	448.7
RIPLEY SOUTH	38 Enercon GmbH E82 turbines	221.8
UNDERWOOD	Unknown	21.6
Total–wind		1,409

Table 15 Full life cycle GHG intensity for Ontario wind farms in 2008

Facility name	GHG intensity (t CO_2e/GWh)				
	Const.	Trans.	Oper.	Decom.	Full life cycle
AMARANTH	6.97	3.44	0.74	0.27	11.42
KINGSBRIDGE	6.97	4.25	0.74	0.27	12.23
PORT ALMA	6.97	1.05	0.74	0.27	9.03
PORT BURWELL	6.97	3.02	0.74	0.27	11.00
PRINCEFARM	6.97	2.50	0.74	0.27	10.48
RIPLEY SOUTH	6.97	3.86	0.74	0.27	10.32
UNDERWOOD	6.97	3.02	0.74	0.27	10.32
Total–wind	6.97	3.02	0.74	0.27	10.69

paper (181 t CO_2e/million tkm). It was assumed that each turbine would be in operation for approximately 20 years, which permitted the calculation of an annual GHG emission rate and intensity for the transportation of the turbines from the manufacturer to the installation site.

The GHG emissions associated with the decommissioning of wind turbines are not well understood in the Ontario context, though they have been reported in LCA studies for other jurisdictions. It was assumed that the GHG intensity for decommissioning wind turbines in Ontario would be the same as the GHG intensity for decommissioning turbines cited in other studies. The decommissioning GHG intensity was calculated as 0.27 t CO_2e/GWh using data provided in a LCA of wind turbines in the U.K. (Feng et al. 2010). The full life cycle GHG emission factors for each wind farm are provided in Table 15.

The life cycle GHG intensity for the wind farms in Ontario ranges from 9 to 12 t CO_2e/GWh, and the weighted average intensity for the wind category is approximately 11 t CO_2e/GWh. It is worth noting that the weighted average for wind sources of electricity in this study (11 t CO_2e/GWh) is also at the lower end of the range cited in the literature (11 to 120 t CO_2e/GWh). The low life cycle GHG intensity for this category is likely a result, at least in part, of using data relating to onshore turbines, rather than the more energy- and material-intensive offshore turbines.

3.7 Summary

This section of the paper provides a summary of the findings for each of the electricity generation categories. Table 16 provides a high level summary of the life cycle GHG intensities, annual electricity generation and annual life cycle GHG emissions of the entire Ontario grid in 2008. The 'Life Cycle GHG Intensity' of each *type* of electricity generation facility is presented in the table. The GHG intensity of the total Ontario grid (shown as 'Ontario total') is also presented. Total 'Life Cycle GHG Emissions' for each source category was calculated by first multiplying the life cycle GHG intensity for each facility by the total electricity

Table 16 Summary of 2008 Ontario electricity generation and life cycle GHG emissions

Type of generation	Electricity generated (GWh (%))	Life cycle GHG emissions (t CO_2e)	Percentage of total GHG emissions (%)	Life cycle GHG intensity (t CO_2e/GWh)
Oil and gas (Lennox)	370 (0.3 %)	400,486	1.3	1,082
Black coal–sub-bituminous	22,047 (14.0 %)	23,374,686	75.0	1,040–1,069
Brown coal–lignite	1,068 (0.7 %)	1,351,989	4.3	1,223–1,360
Coal–total	23,115 (14.7 %)	24,726,675	79.3	1,069
Natural gas–SCGT/CCGT	7,830 (5.0 %)	3,663,999	11.8	351–704
Natural gas–CHP	3,125 (2.9 %)	1,538,494	4.9	417–707
Natural gas–total	10,955 (7.0 %)	5,202,493	16.7	497
Hydro–run of river	1,044 (0.7 %)	1,566	0.0	2
Hydro–reservoir	36,541 (23.3 %)	822,177	2.6	23
Hydro–total	37,839 (24.0 %)	823,743	2.6	22
Wind–total	1,409 (0.9 %)	15,109	0.05	11
Nuclear (CANDU–HWR)	83,380 (53.1 %)	400,224	1.3	5
Ontario total	157,068 (100.0 %)	31,168,243	100	201

generated for each facility to find the total life cycle GHG emissions for each facility in 2008. Then, the life cycle GHG emissions for each facility were summed for each source category and for the entire grid.

The life cycle GHG intensity of the entire Ontario electricity grid is 201 t CO_2e/GWh. As expected, this is slightly higher than the reported 170 t CO_2e/GWh on the Environment Canada website because this study included the GHG emissions associated with the entire life cycle, rather than just the operational stage, for each Ontario facility in 2008.

4 Conclusions

This study provides a facility-specific life cycle assessment of GHG emissions related to the generation of electricity in Ontario in 2008. This analysis was conducted to help inform decisions relating to electricity system operation, energy policy and GHG emission calculations in the province of Ontario. Although some previous studies relating to Ontario and other jurisdictions have estimated GHG emission factors by electricity generation technology type, this work provides site-specific emission factors in an effort to more precisely measure the global warming impact of electricity generation in Ontario. It is recognized, however, that the Ontario government continues to pursue policies to decarbonise the electricity system, such as phasing out coal facilities by 2014 and implementing a feed-in-tariff to expand renewable generation of electricity (e.g. wind and solar). The results reflect only the global warming impact of electricity generation, and they are meant to inform a broader discussion which includes other environmental, social, cultural, institutional and economic factors. This full range of factors should be included in decisions regarding energy policy for the Province of Ontario, and in future work on the Ontario electricity system.

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